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Climate change and water table fluctuation: Implications for raised bog surface variability

Julius Taminskas [a], Rita Linkevičienė [a,b], Rasa Šimanauskienė [a,b,*], Laurynas Jukna [b], Gintautas Kibirkštis [c], Marija Tamkevičiūtė [a]

[a] Nature Research Centre, Akademijos str. 2, Vilnius, Lithuania
[b] Faculty of Chemistry of Geosciences, Čiurlionio str. 21/27, Vilnius University, Lithuania
[c] Čepkeliai-Dzūkija PAN Park, Vilniaus str. 3, Merkinė, LT-65334 Varėna District, Lithuania

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ABSTRACT

Cyclic peatland surface variability is influenced by hydrological conditions that highly depend on climate and/or anthropogenic activities. A low water level leads to a decrease of peatland surface and an increase of C emissions into the atmosphere, whereas a high water level leads to an increase of peatland surface and carbon sequestration in peatlands. The main aim of this article is to evaluate the influence of hydrometeorological conditions toward the peatland surface and its feedback toward the water regime. A regional survey of the raised bog water table fluctuation and surface variability was made in one of the largest peatlands in Lithuania. Two appropriate indicators for different peatland surface variability periods (increase and decrease) were detected. The first one is an ~200 mm y^{-1} average net rainfall over a three-year range. The second one is an average annual water depth of 25–30 cm. The application of these indicators enabled the reconstruction of Čepkeliai peatland surface variability during a 100 year period. Processes of peatland surface variability differ in time and in separate parts of peatland. Therefore, internal subbasins in peatland are formed. Subbasins involve autogenic processes that can later affect their internal hydrology, nutrient status, and vegetation succession. Internal hydrological conditions, surface fluctuation, and vegetation succession in peatland subbasins should be taken into account during evaluation of their state, nature management projects, and other peatland research works.

1. Introduction

The nature of peatlands is controlled by hydrological processes, and normally, their formation begins in moist depressions. These depr are filled with partially decayed litter, and thus, peatland grows upward and expands laterally (Korhola, 1992; Franzén, 1994; Almquist-Jacobson and Foster, 1995; Franzén et al., 1996; Korhola et al., 1996; Yu et al., 2000). Afterward, peatland transforms into a raised bog phase. The surface of the raised bog depends on the organic mass balance. The raised bog shape and the notion of its change are based on several assumptions: (i) peat accumulation is faster at the bog centre resulting in a convex shape of the peatland surface; (ii) raised bog surface height is a function of its age and the rate of peat accumulation decreases over time; and (iii) a raised bog is drained by streams, which are fed by a constant area of peatland. These assumptions are mainly based on *the bog growth model* (BGM) (Clymo, 1984) and *the groundwater mound hypothesis* (Childs and Youngs, 1961; Ingram, 1982). Both hypotheses make predictions for large-scale patterns (e.g., a huge peatland complex) and long-term peatland dynamics (e.g., Holocene period) (Yu et al., 2001). The changes of the peatland surface will have a constant character as the bias of the peat age detection is ~100–200 years (Mažeika et al., 2009). However, the small-scale (e.g., a part of peatland) and short-term research (e.g., up to 100 years) show the intensive fluctuation of the peatland surface (Franzén, 2006). Observations on European peatlands (Ingram, 1983; Weber, 1902; Glaser et al., 2004) describe seasonal or annual fluctuations of peatland surfaces in the range of 10–30 cm. More recent research suggests that peatland surface fluctuations occurring from +18 to −43 cm could be observed over a short time series (during several decades) (Franzén, 2006). However, the peatland surface changes over the long time scale will approach the rate of peat addition to catotelm, i.e., ca. <1 mm y^{-1} (Belyea and Baird, 2006), and must not be related to a seasonal phenomenon but to longer-term hydrological fluctuations (Almendinger et al., 1986; Feurdean et al., 2015).

Although the bog growth model and the groundwater mound hypothesis were landmark advances of their time, a hierarchical approach to modelling could lead to a better representation of peatland development and a response to external forcing (Belyea and Baird, 2006).

* Corresponding author at: Nature Research Centre, Akademijos str. 2, Vilnius, Lithuania.
E-mail addresses: julius.taminskas@geo.lt (J. Taminskas), rita.linkeviciene@geo.lt (R. Linkevičienė), rasa.simanauskiene@gf.vu.lt (R. Šimanauskienė).

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Moreover, the rate of peat production and decay is different in the acrotelm and catotelm. Acrotelm, which is the upper oxic layer (stratum), is a product of several decades and indicates microforms of peatland; whereas catotelm, which is the underlying anoxic layer, reflects mezoforms of peatland (Holden and Burt, 2003; Baird et al., 2016).

The constant accumulation of organic material in the catotelm (Clymo, 1984) influences the augmentation of the peat layer at 1 mm y^{-1} in pristine peatlands (Franzén, 2006). However, our observations imply more rapid changes of the peatland surface, which is influenced by peat accumulation and subsidence. Favourable humidity conditions (high net rainfall) influence a rapid development of peat-forming plants. Moreover, low peat decomposition rates induce a high litter production in the acrotelm. Therefore, the increase of the raised bog surface is up to several cm y^{-1}. Water regime changes (a lack of humidity) in the acrotelm influence the subsidence of peat, and the raised bog surface decreases up to several cm y^{-1}. The main indicators of the raised bog surface variation are average annual excess precipitation (also called net rainfall) and average annual water table depth.

Therefore, the main aim of this article is to evaluate the influence of hydrometeorological conditions toward the peatland surface and its feedback toward the water table depth. This theory implies the dynamics of limits of peatland subbasins and is vitally important for sustainable peatland management and maintenance. The restoration of disturbed peatland habitats requires the ability to comprehend the complex mechanism of peatland renaturalization in the context of the subbasin's level. Methodological applications for peatland restoration after the disturbed hydrological regime are many (Gorham and Rochefort, 2003; Holden et al., 2004; Howie and Meerveld, 2011). However, the lack of a holistic approach in the subbasins level may prolong a recovery of many hydrological and ecological processes for many decades (Price et al., 2003). To date, most of the research on Lithuanian peatlands (Taminskas et al., 2008a; Mažeika et al., 2009; Kažys et al., 2015) concentrates on the influence of climate change toward the hydrological regime and peatland's landscape (Edvardsson et al., 2015). However, no studies are available on peatland surface variation and hydroclimatic interdependencies. Therefore, in this study, we will concentrate on (i) the raised bog surface and subdivision issue and (ii) climate, hydrology, and the raised bog surface variation interrelationships.

2. Study area

Čepkeliai (54°00′N, 24°30′E) is one of the largest peatlands in Lithuania (5858 ha) consisting of raised bogs (82% total area), fens (16%), and transition mires (2%). This peatland consists of 3.2% of all of the natural (nondrained) Lithuanian mires (Taminskas et al., 2012). Several mineral substrate islands and 21 small lakes are located inside this peatland.

Čepkeliai peatland is drained by three streams (Fig. 1): Katra (109 km, the right inflow of the Nemunas River) and the Ūla (84 km) and Grūda (36 km) streams (inflows of Merkys). The Ūla and Katra catchments changed in the middle of the nineteenth century because of natural capture. Accordingly, the discharge changes, transformations of the rivers' longitudinal profiles, and reduction and extinction of lakes in these catchments were observed (Linkevičienė, 2009). No research regarding the capture influence on Čepkeliai peatland surface development was carried out.

The surface of the peatland is slightly undulating (128.5–134.4 m asl). The average depth of the organic layers is ~2.3 m but can locally be as much as 16.5 m.

The average annual temperature is 6.8 °C in this region. The average monthly temperature fluctuates from −3.7 °C in January up to 17.9 °C in July. The average annual rainfall is ~700 mm, and snow cover remains for ~90 days. Annual net rainfall is ~220 mm.

Farming activities are restricted in the whole Čepkeliai peatland and its surroundings, as this territory is covered by different protected area status. The Čepkeliai state strict nature reserve was founded in 1975. It was included in the Ramsar site list as a Wetland of International

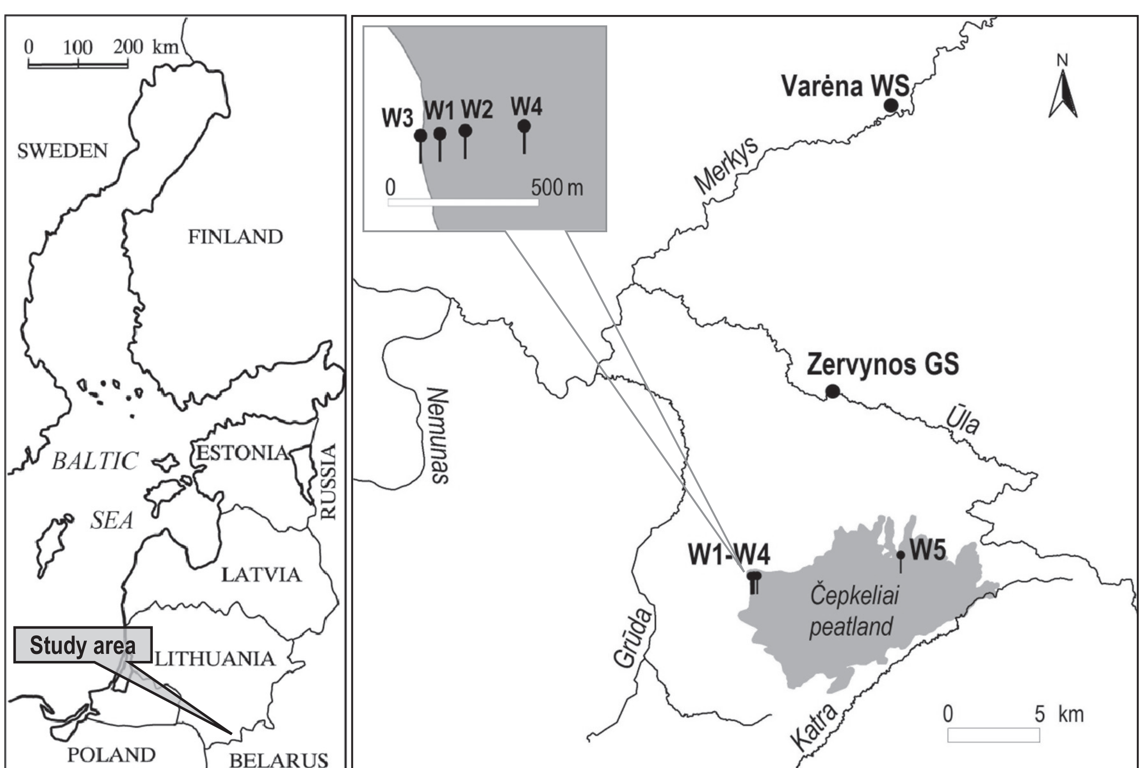

Fig. 1. Location map of the Čepkeliai peatland (WS – weather station; GS – gauging station; W1–W5 – wells).

Importance in 1993. Čepkeliai peatland is also an important part of the European Union ecological network — NATURA 2000 territory.

3. Materials and methods

3.1. Peatland surface and subbasins

LiDAR (*Light Detection and Ranging*) point cloud surface data from the Lithuania surface scanning project and implemented by the National Land Surface Agency of Lithuania in 2007 and topographic maps at the scale of 1:10,000 from 1981 were used for determination of the Čepkeliai surface variation during the period from 1981 to 2007 and the identification of drainage subbasins of peatland. The DEM (*digital elevation model*) data, vector and raster surface elevation layers from the LiDAR point cloud, and topographic maps (after vectorization) were processed and calculated with ArcGIS 10.4 version. The data were used for further analysis, identification of drainage subbasins, and scale of the surface changes.

Absolute values of peatland surface changes were not analysed in detail because of the different accuracies of the LiDAR point cloud surface data and topographical maps. These values were generalized into three surface change classes: slight increase (≥+0.1 m), slight decrease (≤–0.1 m), and no changes (−0.1–+0.1 m). Based on these changes, the peatland surface variability map was formed.

To detect the discontinual character of peatland moisture conditions, a terrain recognition and cartographical interpretation of the desiccation areas of peatland pine trees (Fig. 4) was made in 2012–2013.

3.2. Peatland water table and surface variability

Water table fluctuations in Čepkeliai peatland were analysed according to the data of five wells (W1, W2, W3, W4, and W5) located in the northwestern and north-central parts of the raised bog. The W1 well is located at 65 m, the W2 well at 155 m, the W3 well at 10 m, and the W4 well at 300 m from the western margin of the peatland. The W5 well is located 450 m from the north margin of the raised bog (Fig. 1). Long-term (2002–2016) peatland surface elevation and water table measurements were made only in the W1 and W2 wells. These measurements are valuable for showing the long-term relationship between peatland surface elevation and the water table. The measurement period is comprised of dry and wet years. However, long-term measurements were affected only in two wells that are located close to each other.

In other wells (W3, W4, and W5), short-term measurements (2–5 year period) were made during 2002–2016. They are located in other parts of the peatland and their measurements enable an evaluation and verification of the W1 and W2 results.

The water table in all of the wells was measured during the vegetation period (April–October). Measurements were made manually and every 10 days with an accuracy of 1 cm. According to these measurements, the average annual water table was calculated. Water table reconstruction is based on the long-term water table measurements in W1 and W2 (H_1 and H_2, m asl).

The peatland surface variability was analysed in correspondence with the W1, W2, W3, W4, and W5 measurements. The surface elevations near the wells were measured manually and every 10 days with an accuracy of 1 cm during the vegetation period (April–October) of 2007–2016. According to these data, the average annual surface elevation was calculated (*SE*, m asl).

According to the difference between the water table and the peatland surface elevation, the average annual water depth (*d*, m) during 2007–2016 was calculated in all of the wells: $d = H – SE$.

An analysis of the climate indices were made according to precipitation and air temperature measurements made at the Varėna weather station (WS) during 1929–2016. The Varėna WS is located 27 km to the north of the Čepkeliai peatland centre (Fig. 1). Air temperature differences between the peatland and WS are insignificant. However, precipitation, especially heavy rain, may slightly differ in the Varėna WS and Čepkeliai peatland. According to Varėna WS precipitation measurements, the average annual precipitation (*P*, mm) was calculated. The temperature data were used to calculate the potential evapotranspiration (*PET*, mm) according to the Thornthwaite (1948) equation. Thornthwaite's equation is based entirely upon a temperature relationship, has the disadvantage of a rather flimsy physical basis, and has only theoretical justification (Taylor and Ashcroft, 1972). Because the temperature and vapour pressure gradient are modified by the movement of air and by the heating of the soil and surroundings, the formula generally is not valid but must be tested empirically whenever the climate is appreciably different from areas in which it has been tested in original spatial and temporal contexts (Skaggs, 1980; Nokes, 1995; Xu and Singh, 2001). However, no measurements have been made of the net radiation since 1929 in the Varėna WS. Therefore, the evaluation of evapotranspiration from the peatland was complicated, and Penmans' or Priestly-Taylor formulas (Sumner and Jacobs, 2005), although very appropriate, could not be used in our case. However, prior research (Taminskas et al., 2008b) showed a reliable relationship (R^2 from 0.57 to 0.62) between estimated actual evapotranspiration and potential evapotranspiration estimated according Thornthwaite's equation in the territories near our study area.

Net rainfall (*NR*, mm) was calculated after the evaluation of the difference between average annual precipitation and potential evapotranspiration. The net rainfall (*NR*) for the year *i* is also known as the average annual excess and provides a simple measure of the water surplus or deficit for the analysed year: $NR_i = P_i – PET_i$. Long-term (2, 3 and 4 years) average NR, NR_2, NR_3, and NR_4 was also used for further analysis.

Linear relationships between the measured values of the peatland water table (H_1 and H_2) and *NR* of the different periods were analysed. According to the analysis of these relationships, an average annual water table in W1 and W2 wells during 1930–2016 was reconstructed (H_{1r} and H_{2r}, m asl).

To evaluate the peatland surface variations, the annual peatland surface elevation gradients (ΔSE: $\Delta SE_n = SE_{n+1} – SE_n$) were calculated according to the average annual surface elevation (SE_n). To reconstruct the peatland surface variation during the longer period, a reliable relationship between the surface variation and *NR* during 2007–2016 was detected. According to this relationship, the peatland surface elevation from 1930 to 2016 was reconstructed near the W1 and W2 wells (SE_{1r} and SE_{2r}, m asl). The average annual water depth was reconstructed in relation to the reconstructed peatland surface elevation and reconstructed average annual water table (d_{1r} and d_{2r}, m).

To evaluate the results derived from the W1 and W2 wells, relationships between NR, d, and SE in the short-term wells (W3, W4, and W5) were analysed.

Ūla stream runoff data from the Zervynos water gauging station (GS) during 1960–2015 were used for verification of the reconstructed peatland water table and surface change. Ūla is one of three streams that drain the Čepkeliai peatland. Zervynos GS is situated ~25 km downstream from the Čepkeliai peatland (Fig. 1). After analysis of the relationship between the average annual water depth in the peatland (*d*) and various indices of draining stream runoff, the strongest correlation was found with the annual minimum of 7 days of runoff (Q_{7min}, $m^3\ s^{-1}$). This index of draining river runoff was used for verification of the reconstructed water table and surface elevation of the peatland.

4. Results

4.1. Peatland surface and subbasins

Elevation of the Čepkeliai peatland surface is approximately 129–135 m asl The raised bog is located in the northern, western and eastern parts of the peatland. The central part of the raised bog is >132 m asl, whereas the highest elevation point is located in the west of the raised

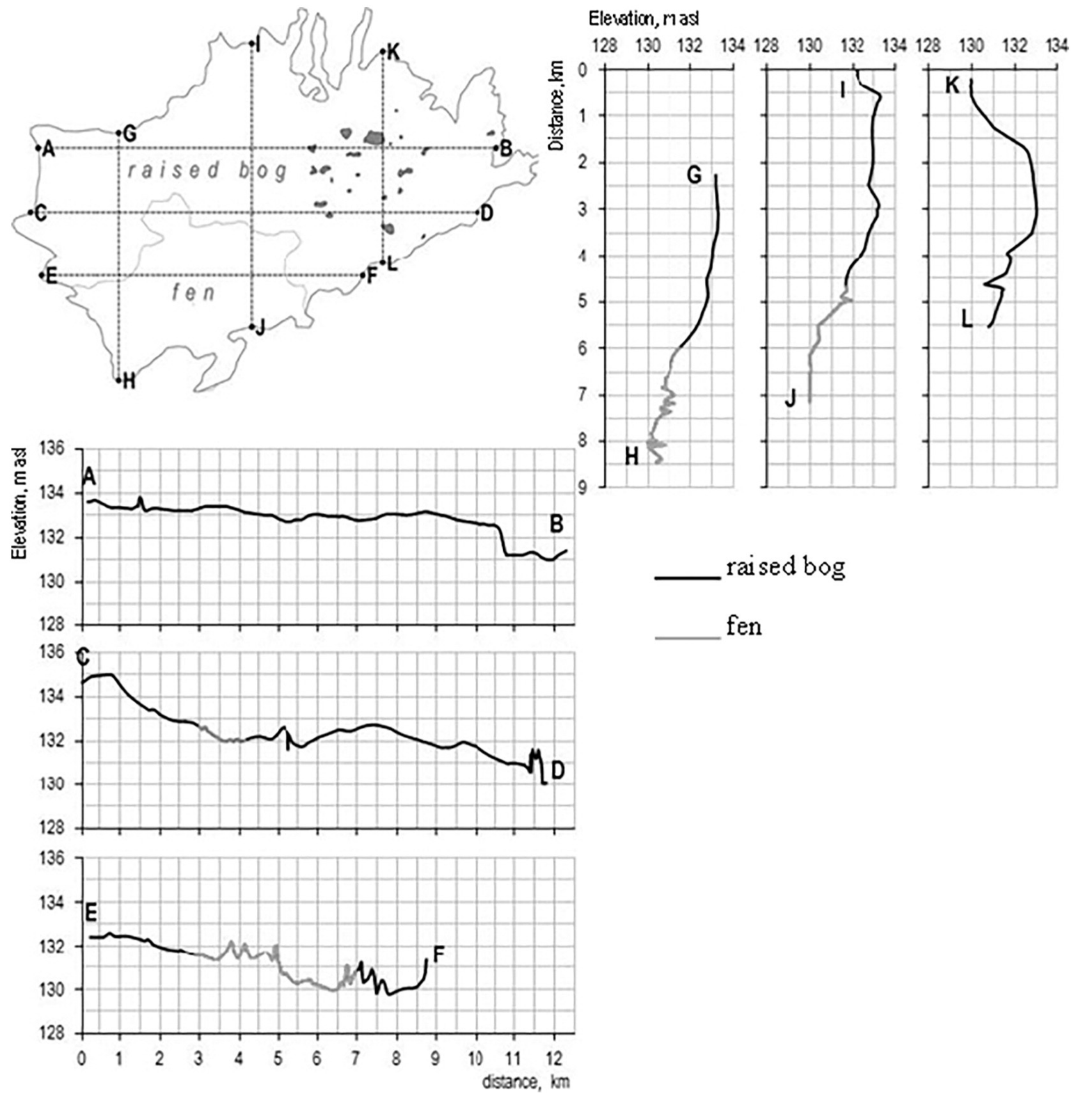

Fig. 2. Čepkeliai peatland profile graphs.

bog (>134 m asl). The surface is lower and more undulated in the margins of the raised bog and fen that are located in the southern part of the peatland (Fig. 2). According to the raised bog profile graphs, the surface does not continuously increase to the centre. Rather, it is more undulated with the appearance of hollows and hillocks. The groups of hollows form watersheds of the subbasins.

The surface of the Čepkeliai peatland increased in the past few decades (Fig. 3). Only in a few areas in the Katra subbasin, mainly in the fen, can the decrease of the surface be observed. The surface variation was from −1.8 to +1.9 m when comparing the topographical map (1981) and LiDAR data (2007). Thus, the average annual change was ±7 cm in the areas of the fastest surface variability.

In the plain watershed surface of the peatland, even small differences in elevation influence surface runoff distribution and water storage in the different subbasins. Peculiarities of the water regime, vegetation development, and peat formation in different parts of the peatland are a function of insularity of these subbasins and the conditions of the surface runoff. Seven parts have different draining conditions in the Čepkeliai peatland: the Ūla, Grūda, and Katra subbasins, in which water runs to the rivers; and four closed drainage subbasins, where water surplus is removed by groundwater exchange or evapotranspiration (Fig. 4). The probable differences of hydrological conditions in the subbasins reflect the pine desiccation phenomenon in a closed subbasin that is located in the northwestern part of the peatland (Fig. 4). No pine desiccation was detected in other parts of the peatland.

4.2. Climate, hydrology, and peatland surface variation

Overland flow and throughflow are the main causes of water loss in raised bogs. However, the water table depends on the main water balance elements, which are precipitation and evapotranspiration. Long-term change and periodical fluctuations of the water balance elements mostly influence the inequality of the water table in the peatlands and the development of the other processes. Existing meteorological data enable the evaluation of three-decade climate normals and comparison of the humidity conditions during these periods in the Čepkeliai peatland (Table 1).

Differences of *NR* show various conditions of peatland humidity during the three-decade period and in separate years. According to the graph (Fig. 5), the rotations of the dry or wet year sequences of the different lengths prevail. This influences long-term transformations of the

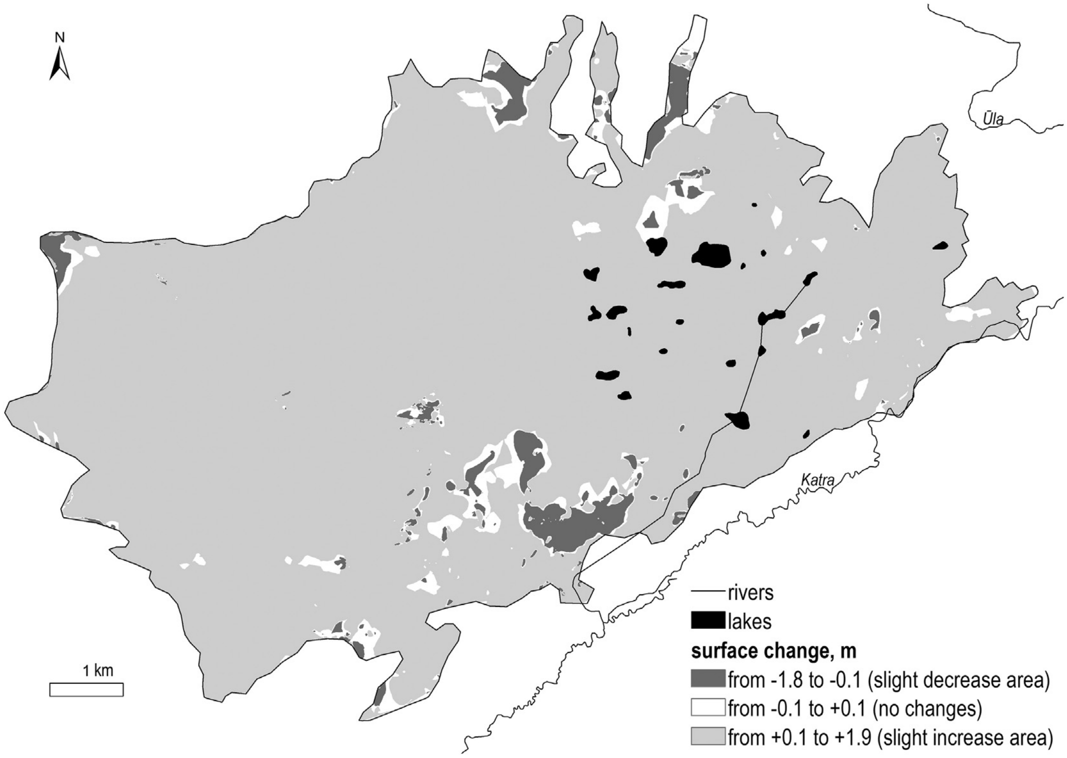

Fig. 3. Transformation of the Čepkeliai surface during 1981–2007.

peatland groundwater table and surface. For example, the dry period during 1959–1988 was not favourable for the surface increase: a low net rainfall induced the processes of surface decrease. However, two periods with high net rainfall were observed during 1989–2016 with a short interruption of lower net rainfall in the 1990s (Table 1, Fig. 5).

Fluctuation of the average water table in the wells corresponds to net rainfall in the same year (Fig. 5). However, a weak relationship between the average annual water table (H_1 and H_2) and annual precipitation, *PET* and *NR*, is observed. The correlation coefficient between annual *NR* and the average water table is 0.101 (NR/H_1) and 0.313 (NR/H_2). A weak relationship also occurs between the average annual water table and net rainfall (NR_2 and NR_3). A possible explanation for this might be that the water table of previous years was not included in the evaluation process. A strong relationship is observed only between NR_4 and the average annual water table in the wells: $R = 0.616$, $p < 0.05$ (W_1) and $R = 0.685$, $p < 0.01$ (W_2).

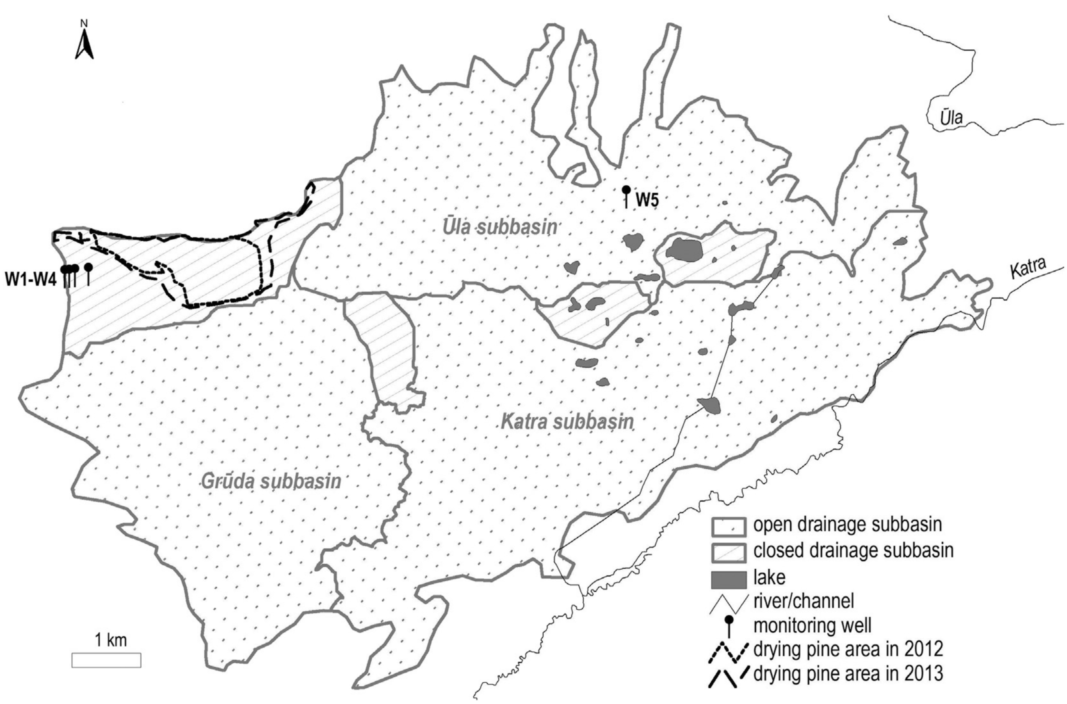

Fig. 4. Situation of the subbasins in 2007 in the Čepkeliai peatland.

Table 1
Hydroclimatical indices are calculated according to the Varėna WS 1929–2016 data.

Index	Period					
	1929–2016			1929–1958	1959–1988	1989–2016
	Min	Max	Avg	Climate normals		
P, mm	423	874	680	686	654	701
PET, mm	414	511	469	464	462	481
NR, mm	−43	423	211	222	192	220

A strong and significant relationship is observed between the average annual water depth and the net rainfall of the two years (NR_2):

in the first well $R = 0.714, p < 0.05, d_{1r} = 0.0009\ NR_2 – 0.463$ (1)

in the second well $R = 0.759, p < 0.05, d_{2r} = 0.0006\ NR_2 + 0.395$ (2)

This confirms that the relationship between net rainfall and the water table is weak. However, it has a strong character if we take into account net rainfall and water depth. Such differences could be explained by the significant influence of water depth toward evapotranspiration.

The water depth in wells W1 and W2 (d_{1r} and d_{2r}) was reconstructed according to Eq. (1) and Eq. (2) during 1930–2016 (Fig. 6). The analysis of the relationship between the reconstructed water depth and the peatland draining river flow showed a strong correlation with annual 7-day minimum flow ($R = 0.562$, $p < 0.00001$). Therefore, the minimum annual flow is appropriate for evaluation of the peatland water storage.

According to the measurements, the peatland surface variability may have a high amplitude and may be characterized by different trends. It depends on various factors such as vegetation productivity, the amount of litter and its level of decomposition, and acrotelm subsidence. Most of these factors are linked directly with the water table. It is critical for peatland development because it controls species composition through anoxia at depth, which retards decomposers and enables peat accumulation (Price et al., 2003). Meteorological conditions influence peat accumulation. In addition, the net accumulation of peat can occur if the summer water deficit is <100–150 mm (Maltby and Proctor, 1996). Our research confirms the proposition that the raised bog surface variability depends on annual net rainfall. A comparison of the annual surface elevation gradient (ΔSE) of the Čepkeliai peatland with the average value of NR_3 showed that the peatland surface increased when the 3 year net rainfall average was >196–209 mm y^{-1}, ca. $NR_3 > 200$ mm (Fig. 7).

Therefore, when the annual net rainfall is >200–220 mm, the peat surface increases; whereas the decline of the annual net rainfall (<200–220 mm) determines the decrease of the surface (Fig. 7). These intervals were derived according to the analysis of long-term measurements (W1, W2). A significant influence of the net rainfall toward peatland development was mentioned in earlier studies: no bogs occur in those regions of Ireland where the average annual net rainfall is <250 mm (Hammond, 1984).

Additionally, a strong linear correlation ($R = 0.728$; $p < 0.05$) was detected between ΔSE and NR_3 near the short-term wells W3, W4, and W5. However, the measurements in these wells were only taken during the increased surface periods. Therefore, hydroclimatical conditions influencing the surface decrease could be detected only according to the linear relationship. The surface decrease in these wells should be observed when $NR_3 < 186$ mm (Fig. 8). Such differences compared to the abovementioned results are influenced by a small set of data. It might also be influenced by the difference of surface and hydrological conditions: W1 and W2 wells are located in the slope of peatland, W3 (near lagg), and W4 and W5 (in the flat part of the peatland).

According to the net rainfall, wet ($NR > 200$ mm) and dry ($NR < 200$ mm) years were distinguished. A wet year prevailed in 1929–2016, and the trend of the peatland surface increase was observed. Dry years prevailed in the 1960s and 1970s (Fig. 5). A significant decrease of the peatland surface is observed in this period, and the question arises as to what could evoke vegetation succession (a rapid overgrowth of peatland with woody vegetation) (Edvardsson et al., 2015).

Surface increase and decrease cycles were observed in the Čepkeliai peatland during 2007–2016. In this period, a strong linear correlation was detected between the annual peatland surface elevation change (ΔSE) and the water depth (d) in the W1 and W2 wells: $R = 0.739$, $p < 0.05$ ($\Delta SE_1/d_1$), $R = 0.734$, $p < 0.05$ ($\Delta SE_2/d_2$). According to these relationships, the peatland surface decrease replaced the increase and vice versa when the average annual water table was ~27–30 cm (Fig. 9). The water depth decline leads to the acceleration of the peatland surface increase. The fastest peatland surface increase, which was 7 cm y^{-1}, was detected in 2011 when the average annual water depth was 20–21 cm (Fig. 9, W1). The fastest decrease, which was nearly 6 cm y^{-1}, was in 2014 when the average annual water depth was 27–29 cm (Fig. 9, W2).

Another kind of relationship appeared between water depth in the W3, W4, and W5 wells and surface elevation. Additionally, the strong linear correlation ($R = 0.769$, $p < 0.05$) between d and NR_3 near the wells is observed according to these measurements (Fig. 10). However, as mentioned above, no measurements were made in these wells during the dry and surface-decreasing periods. Therefore, the linear correlation only shows that the surface decrease appears when the water depth declines <15 cm in the wells. Measurements of the W3, W4, and W5 wells are excluded from the retrospective analysis because of the short period and different surface and hydrological conditions.

The annual variability amplitude of the peatland surface near W1 well was from −6 up to +6 cm. The amplitude of the farther well W2

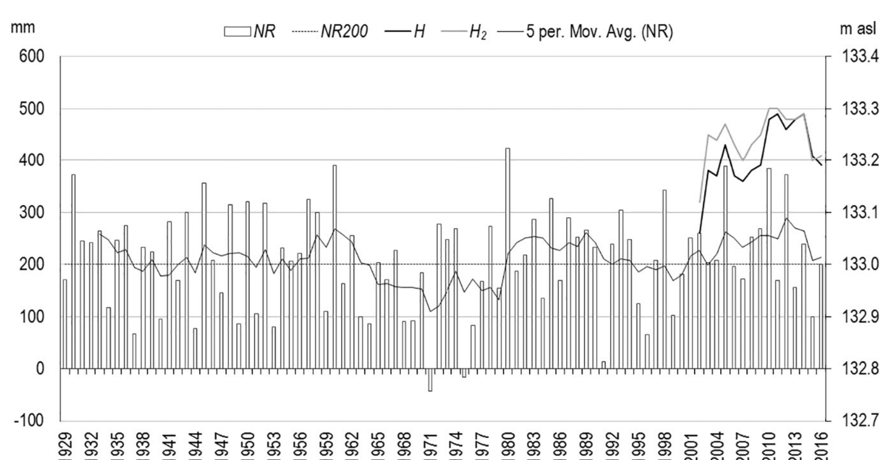

Fig. 5. Fluctuation of the measured water table (H_1 and H_2) in the Čepkeliai peatland wells and net rainfall (NR).

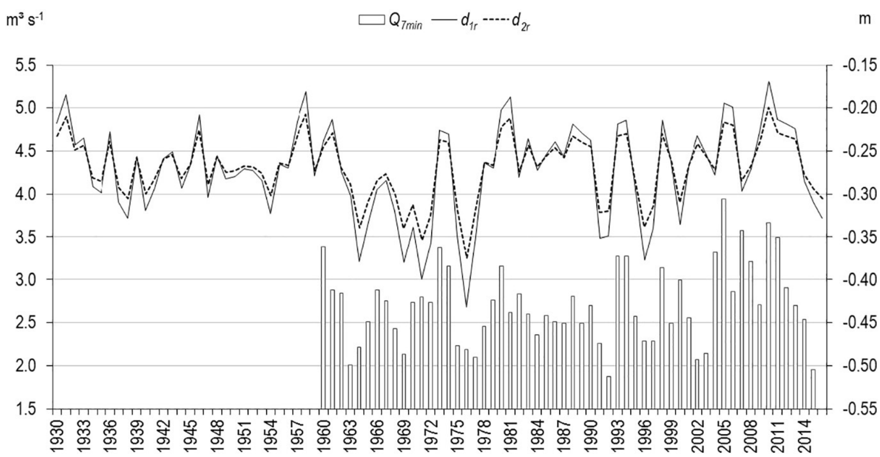

Fig. 6. Fluctuation of the reconstructed water depth of the Čepkeliai peatland (d_{1r} and d_{2r}) and minimum annual 7 day flow of the Ūla River (Q_{7min}).

was smaller and was from -6 up to $+4$ cm y^{-1}. Although the peatland surface varied differently near the W1 and W2 wells in separate years, the trend of the surface variability was the same.

The variability amplitude of the peatland surface increase or decrease according to *NR* (Figs. 7 and 8) and *d* (Figs. 9 and 10) corresponds to the specific case and the limited set of our observations. Additional research is needed to specify these limits and to determine the application possibilities in other raised bogs.

Analysis of the minimum 7 day annual Ūla flow (Q_{7min}) was performed to evaluate the relationships between the river flow and the peatland surface variation. The results showed a very similar variation of the minimum flow and estimated the annual surface elevation gradient (ΔSE) (Fig. 11). The peatland surface increases during the wet years, which is detected by the 7-day minimum annual river flow ($Q_{7min} > 3.7$ m^3 s^{-1}).

The correlation coefficient between the raised bog annual surface elevation gradient and net rainfall (*NR*, NR_2) varies from 0.606 up to 0.663 ($p < 0{,}1$). A higher correlation and a positive relationship ($R = 0.782$, $p < 0.05$, $\Delta SE_{r1} = 0.0489\ NR_3$–9.58) was obtained between the annual surface elevation gradient ΔSE close to the W1 well and average NR_3. A weaker positive relationship was obtained between the annual surface elevation gradient close to the W2 well ($R = 0.696$, $p < 0.05$, $\Delta SE_{r2} = 0.0446\ NR_3 - 9.336$). Therefore, the annual surface elevation gradient of the raised bog was calculated according to NR_3. The reconstructed peatland surface (SEr_1 and SEr_2) is based on the calculations of the annual surface elevation gradient (ΔSE_r). Parameters SEr_1 and SEr_2 show that because of favourable humidity conditions, the raised bog surface close to the W1 and W2 wells was increasing during the 1930–2016 period. The surface of the peat increased in the 61 cm (ca. 7 mm y^{-1}) close to the W1 well, whereas an increase of only 4 cm (ca. 0.5 mm y^{-1}) close to the W2 well was estimated. Generally, the surface increased more quickly in the margins of the peatland. Therefore, the reconstructed peatland surface in 2011 close to the W1 well became higher compared with the W2 well that is located farther from the peatland margins (Fig. 11), and according to the measurements it occurred in 2015. Thus, the local direction of the surface slope changed, and a natural barrier for overland flow toward the margin of the raised bog formed.

Analysis of shorter periods showed even different peatland surface variation trends. A fast surface decrease was observed during the 1960s and 1970s: the average annual decrease was ca. 8 mm yr^{-1} near the peatland margin (W1) and even 21 mm y^{-1} farther from the margin (W2). The surface of the peatland increased again during the 1980s: ca. 28 mm y^{-1} (W1) and ca. 17 mm y^{-1} (W2). Development of the peatland surface was rather stable starting from the 1990s up to 2004. It increased 3 mm y^{-1} on average near the peatland margins and it has decreased on average 3 mm y^{-1} farther from margin. A rapid vertical growth of the peatland surface may be observed from 2005: 26 mm y^{-1} (W1) and 16 mm y^{-1} (W2) (Fig. 11). According to the reconstructed surface elevation gradient, the cyclic raised bog surface variability prevails and depends on water storage, which is influenced by local or regional causes in a particular part of the raised bog. From 1970 to 2005 in Swedish raised bogs, the total surface decrease was as much as 17.8 cm or ca. 5 mm y^{-1} (Franzén, 2006). In our case, the reconstructed surface of the Čepkeliai peatland close to the first well (W1) increased insignificantly by only 8.2 cm or ca. 2 mm y^{-1}, whereas the data from the second well (W2) (surface decreased 14.6 cm or 4 mm y^{-1}, Fig. 12) are consistent with the results shown in the abovementioned article. Surface variation close to the peatland

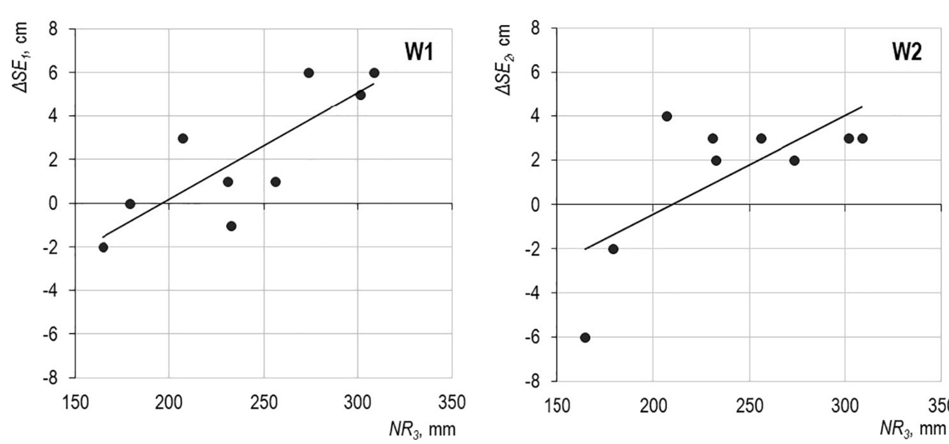

Fig. 7. The relationship between the annual peatland surface elevation gradient (ΔSE) near the W1 and W2 wells and the 3 years of net rainfall average (NR_3).

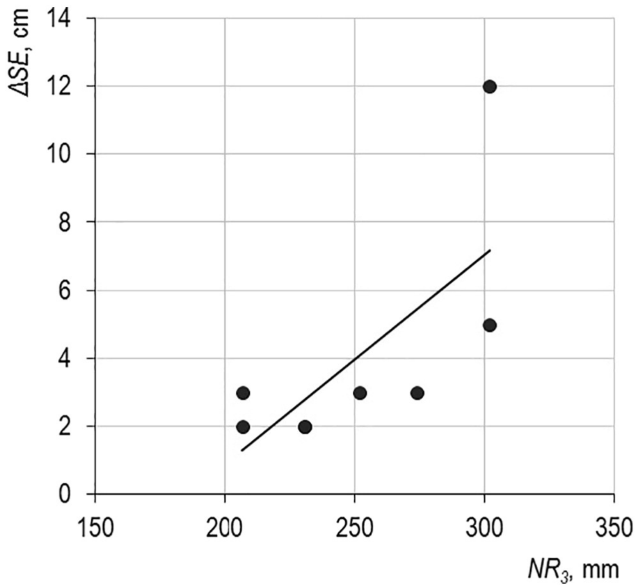

Fig. 8. Relationship between annual peatland surface elevation gradient (ΔSE) near W3, W4, and W5 wells and the 3 year net rainfall average (NR_3).

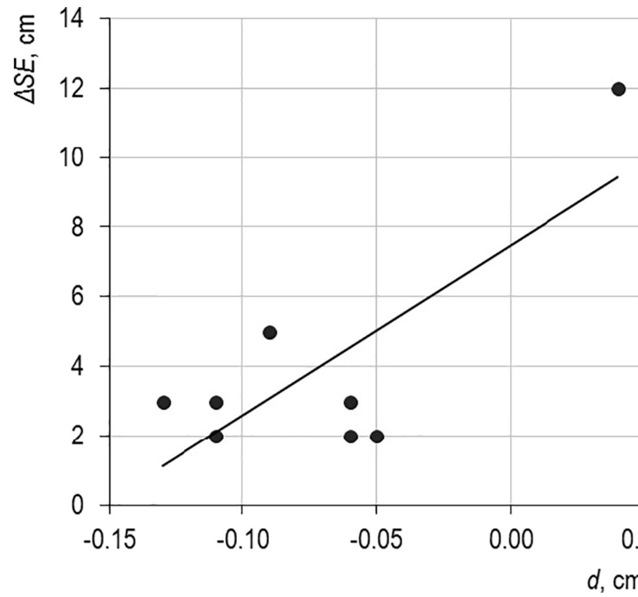

Fig. 10. Relationship between peatland annual surface elevation gradient (ΔSE) near W3, W4 and W5 wells and the estimated average annual water depth (d).

margins (W1) could be influenced by the local water table in the peatland lagg zone, whereas the surface variation near the W2 well could be more affected by meteorological conditions and indicate the surface variability of the bigger part of the peatland. Analysis of LiDAR and topographic maps during 1981–2007 showed that the bigger part of the peatland surface has increased from 0.1 to 1.9 m (Fig. 3). According to surface observation data near the wells (W1 and W2), the reconstructed surface confirms that the Čepkeliai peatland surface increased by 0.16–0.36 m during 1981–2007 (Fig. 12).

5. Discussion

Former studies that have noted the importance of the peat accumulation rate have shown different accumulation results varying from <1 mm up to several mm y^{-1} (Franzén, 2006; Stivrins et al., 2017). A possible explanation for these differences may be the lack of a uniform concept of peat accumulation, i.e., no difference is made between the litter accumulation rate in the acrotelm and the peat accumulation rate in the catotelm. Some previous research analysed peat accumulation rates in the acrotelm and in the catotelm (Belyea and Baird, 2006; Morris and Waddington, 2011; Baird et al., 2016), whereas other studies suggested taking into account only the catotelm peat to determine the peat accumulation rate (Kremenetski et al., 2003; Yu, 2006; Kleinen et al., 2012). Obvious separation of the peatland-forming processes enables us to evaluate the litter-peat accumulation rate and the surface variation more precisely. Our findings are in accord with recent studies; however, the main focus is given to the peatland surface variation. Our results indicate that intensive litter accumulation and low decomposition rates lead to an annual surface increase of a few centimetres. This process is highly influenced by hydrometeorological conditions. A small amount of litter and (or) an intensive decomposition process in the acrotelm may cause a significant peatland surface decrease during certain years. Such a surface variation has a minor influence toward peat accumulation in the catotelm. The litter-peat accumulation rate and peatland surface variability describes different processes. The peatland surface variability depends on the annual amount of litter and aerobic decomposition of litter in the acrotelm, whereas the peat accumulation rates are likely to be related to the annual amount of material that transforms from acrotelm to catotelm and to anaerobic decomposition of this material in the catotelm.

From a hydrology point of view, peatland is usually treated as a homogeneous hydrological system (Ingram, 1983). Other research studies, which are based on relationships of the peatland vegetation and humidity conditions (Lamentowicz et al., 2015), highlight the water regime of the microrelief forms (hummocks, hollows, and lawns) (Foster and Glaser, 1986; Foster et al., 1988; Bubier et al., 1993; Namatēva, 2010;

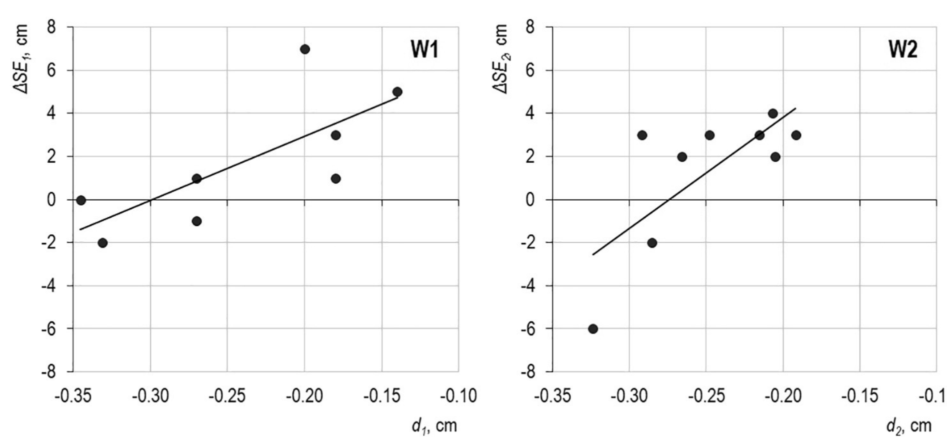

Fig. 9. Relationship between peatland annual surface elevation gradient (ΔSE) near W1 and W2 wells and estimated average annual water depth (d).

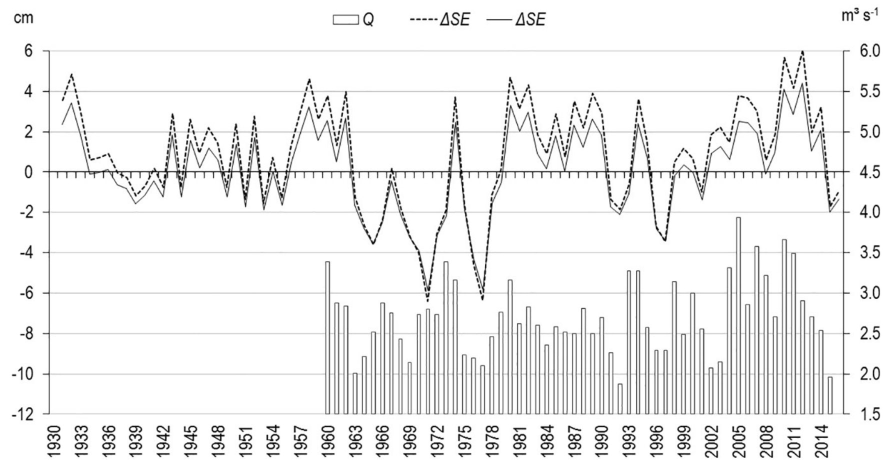

Fig. 11. Fluctuation of reconstructed peatland surface elevation gradient (ΔSE_{1r}, ΔSE_{2r}) and minimum annual 7 day Ūla River flow (Q_{7min}).

Shi et al., 2015). Our research supports the idea that separate parts of the peatland may have an individual water regime. Peatland is divided into separate parts that could be called peatland subbasins. They are separated by microrelief forms that become watersheds for these subbasins. Subbasins involve autogenic processes that can later affect their internal hydrology, nutrient status, and vegetation succession (Hu and Davis, 1995; Swindles et al., 2012; Lavoie et al., 2013). As a result, internal hydrological changes or transitions in these subbasins influence peatland vegetation and peat formation peculiarities (Stivrins et al., 2017). Therefore, we can assume that internal hydrological conditions in the peatlands subbasin level should be taken into account during their state of evaluation, nature management projects, and in other peatland research.

As mentioned above, peatland subbasins influence vegetation succession. Recently, a desiccation of the pine trees was observed in the northwestern part of the Čepkeliai peatland. According to the map of the subbasins, this area coincides with one of them. This finding, while preliminary, suggests that individual water regime changes of this particular subbasin are the main cause of woody vegetation degradation in this area. No similar phenomena are observed in the other parts of the Čepkeliai peatland. Further field and monitoring studies are thus needed to clarify the exact interactions between climate and peatland development, hydrology, and vegetation dynamics.

Peatland surface variability is directly influenced by hydrometeorological conditions (Lamentowicz et al., 2008; Feurdean et al., 2015). Climate change consequences to the Baltic region are well analysed in prior studies (Taminskas et al., 2008a; Kažys et al., 2015; Stonevičius et al., 2017). However, in contrast, few studies (Hilbert et al., 2000) and indicators that enable the evaluation of peatland surface variability have been detected. In regard to this question, our study found two appropriate indicators for different peatland surface variability periods (an increase or decrease). The first one is an ~200 mm y^{-1} average net rainfall in the 3-year range. The second one is the average annual water depth of 25–30 cm. However, short-term measurements in the flat part of the peatland showed a 15 cm value of water depth.

The application of these indicators enabled us to reconstruct the Čepkeliai peatland surface variability during nearly an entire 100-year period. The most obvious finding to emerge from this reconstruction was that the peatland surface variability amplitude was small; however, more significant changes were detected during the shorter periods. Further studies in this and other peatlands, which take these indicators into account, will need to be undertaken before the association between these indicators and peatland surface variability is more clearly understood.

6. Conclusions

Significant climate changes were observed during the last century. This influenced the cyclic fluctuation of net rainfall and water storage in the studied peatland.

When 3 years of the net rainfall average and the annual water depth in a raised bog falls below the limit of the dry years, the bog surface decreases up to few cm per year and vice versa (the bog surface increases when these indicators remain above the dry years limit).

Climate change influences the significant raised bog surface variability in the short time series. However, the average annual surface eventually increases, approaching the rate of peat addition to the catotelm.

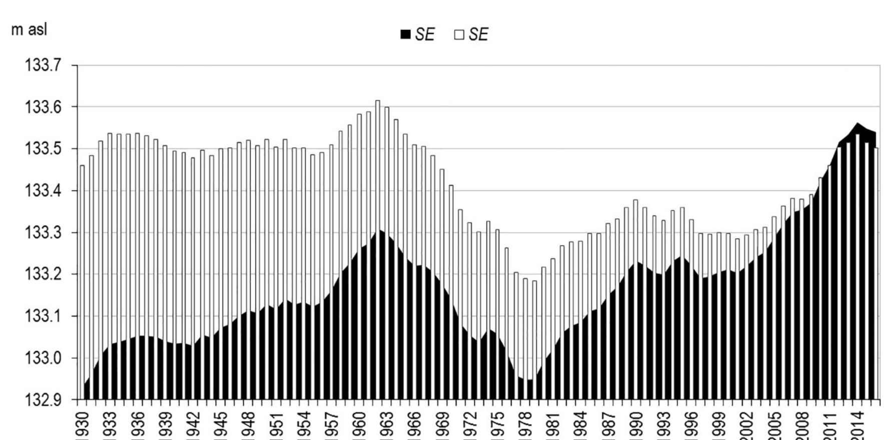

Fig. 12. Variation of the reconstructed surface elevation (SE_1r and SE_2r).

Watersheds of short-term closed or open drainage subbasins may change because of uneven peatland surface variation in the different peatland areas. This may influence the water regime conditions in certain parts of the peatland.

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